



Chapter 5

Food Availability and Stability

Key Chapter Findings

- Climate change influences food availability and stability through many components of the food system.
- The natural-resource base and adaptive capacity each greatly influence food-availability and stability outcomes.
- Climate influences on food production depend on the relative balance of changes being experienced within localized conditions; at the global scale, however, such changes are increasing the challenges to food security.

The first component of food security, *availability*, addresses the question of whether food exists locally. This chapter defines food availability, relates it to important components of the food system, and identifies areas where changes in climate have already influenced and may in the future continue to influence food availability. The chapter addresses the stability of food availability, as well as adaptations for managing changing conditions.

What Is Food Availability?

Food availability requires that sufficient quantities of food be available on a consistent basis. It involves food production, processing, packaging, transport, storage, and all supporting trade systems involved in enabling those activities (FAO 1996, Schmidhuber and Tubiello 2007). This chapter focuses on food production, processing, packaging, storage, trade, and transport as each contributes to food availability.

Food production is the initial creation of food. Following production, all foods are processed to a greater or lesser degree. The foods are then traded and transported to consumers. These components—production, processing, packaging, storage, trade, and transport—work together in many possible combinations to make food available. The food system may be very short—such as a producer who consumes the eggs from chickens that she or he has raised or it may be quite long and involve

many intermediaries, such as produce imported from the Southern Hemisphere during the Northern Hemisphere winter. Both cases illustrate food availability.

5.1 Influences on Food Availability and Stability

Food availability and its stability through time are subject to multiple food-system activities. Where food is, or is not, is a function of production types, rates, and locations. The processing, packaging, and storage of food also contribute to food availability, as do trade and the transportation systems that enable it. Each food-system element is described below, along with climate influences.

5.1.1 Producing Food

Food production occurs through the cultivation of crops and livestock as well as foraging, fishing, and hunting outside of cultivated systems. The relationship of each to climate and weather variables, factors affecting their stability, and anticipated future changes are listed below.

5.1.1.1 Crop Production

Crop production forms the foundation of food availability, providing calories and nutrients for human consumption, as well as feed for animals that contribute to food supplies. At the same time, crop production is vulnerable to climate variability and

change. For example, globally, rain-fed agriculture is practiced on 83% of cultivated land and produces 60% of all food (FAO 2002a). Yet this important form of production is exposed to risk resulting from fluctuations in precipitation.

Agricultural cultivation has expanded gradually over much of the past 10 millennia, but acceleration in productivity since the 1700s has enabled human settlement in most arable regions of the planet (Toussaint-Samat 1992). The subsequent green revolution of the 1960s resulted in the intensification of management, agrichemical, and technical inputs; growth in trade and economic output; changes in land use; and increased yields (Roberts 2008).

Historical production increases have been the result of greater yields (i.e., production per unit area) together with increases in the amount of overall land under cultivation (Funk and Brown 2009; Figure 5.1). Yields have increased globally by about 1.8% per year on average since 2000, resulting in a roughly 20% increase in global cereal production (FAO 2014b) over that time period. The amount of cultivated land per person has decreased by 9% over the same period. The combined effect of these trends has been an 8% increase in total per-capita cereal production since 2000. More recent yield trends are measurably smaller than those of the second half of the 20th century and may in part imply that such historical yield increases are becoming more difficult to attain. In addition, global averages can hide local and regional trends. For example, regions experiencing rapid agricultural expansion, which have strong overlaps with food-insecure regions, experience increased risk due to production

expansion into more arid or other types of less-optimal land (Funk and Brown 2009).

Since 2000, food-production increases have been largely concentrated in countries such as Brazil and China, primarily a result of biotechnology (Paarlberg 2013). In sub-Saharan Africa, investments in agricultural research and wider adoption of new technologies can lead to improved production, though weak scientific capacity and support can hamper those efforts (Fuglie and Rada 2013), and the shrinking size of smallholder farms limits the viability of mechanization (Funk et al. 2008).

Global average yields for the four most-traded food crops (maize, rice, wheat, and soybeans) are stagnating or diminishing on 24%–39% of their growing areas (Ray et al. 2012), and the average global yield growth rates for each (1.6%, 1%, 0.9%, and 1.3%, respectively) lag behind the increases required to meet anticipated mid-century demands (Ray et al. 2013) of a 60%–100% increase in food production (FAO 2009a). Production trends differ in different locations. Eastern Asian rice and northwestern European wheat account for 31% of total global cereal production, but yields in these regions are declining or stagnating as they approach their biophysical limits and face pressures from land degradation, weather, and limits on fertilizer and pesticide use (Grassini et al. 2013). Annual yield increases in China, India, and Indonesia are 0.7%, 1.0%, and 0.4%, respectively (Ray et al. 2013). Annual increases at these levels would increase production by 67% for maize, 42% for rice, 38% for wheat, and 55% for soybeans by 2050 in these countries (Ray et al. 2013), which is generally inadequate to meet anticipated need. In the three largest wheat-producing nations—China, India, and the United States—yields have been increasing at annual rates of 2.7%, 1.1%, and 0.8%, respectively (Ray et al. 2013). The aggregate effects of these yield growth rates would see 2050 wheat yields of 154%, 47%, and 32% compared with current levels for each of these countries, respectively. Wheat yields are in decline across much of Eastern Europe (Ray et al. 2013). In contrast to plateauing yields in capital-intensive systems, slow growth or stagnation is occurring in many low-yield nations where farmers lack access to basic agricultural inputs (e.g., fertilizers), infrastructure, markets, and extension services (Grassini et al. 2013). Compared with major staple crops, less work has been done on the production of specialty crops such as vegetables, tree crops, fruit and ornamentals, livestock, or fish, which can be particularly important in developing regions (Zhang and Wilhelm 2011), and therefore represent an important area for future investigations.

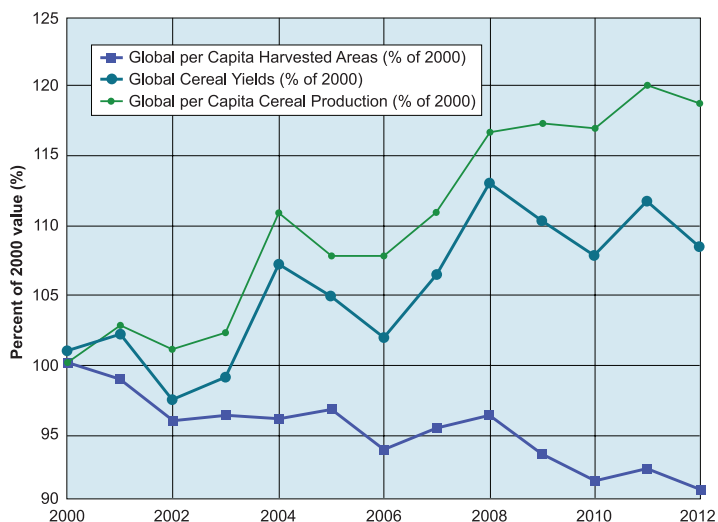


Figure 5.1 Global cereal production, yield, and harvested area relative to year 2000. Global per-capita cereal yields have increased since 2000, even as the trend in per-capita harvested area has decreased. Source: FAO 2014b.

Climate and weather influence food production. Climate and weather influence yields directly through physiological changes under varying temperature and moisture levels and indirectly by altering pest and disease pressures (Malcolm et al. 2012, Sexton et al. 2009, Sutherst 2001).

Temperature, precipitation, atmospheric CO₂ concentrations, soil moisture, and nutrient availability interact to determine how successfully a crop will germinate, flower, and produce seed (Badeck et al. 2004, Chmielewski et al. 2004, Tao et al. 2006). Different crop species and varieties have varying abilities to cope with differing stressors (Chaves et al. 2002); climate change and weather variability will therefore affect different crops, varieties, regions, and production systems in different ways.

Every crop and crop variety has a range of optimal growing and reproductive temperatures, as well as threshold temperatures beyond which the necessary physiological processes cannot occur, causing yields to suffer or cease (Walthall et al. 2012). While net global crop yields are increasing, the effects of recent climate trends may be slowing the rate of increase. Changes in climate may be diminishing rates of yield growth by up to 2.5% per decade, globally (Porter et al. 2014). Yields of corn, soybeans, and wheat in the United States have been shown to increase with temperatures up to 29–32 °C (depending on the crop), and then decrease sharply for all three crops (Schlenker and Roberts 2009). Increased temperatures in China between 1980 and 2008 appear to have reduced yield-growth rates for wheat and corn by approximately 1.5%, though had little effect on the yield-growth rates of rice or soybeans (Tao et al. 2012). In India, increasing minimum temperatures reduced rice yield-growth rates by more than 5% between 1960 and 2002 (Auffhammer et al. 2012).

Crops grown in warmer climates (e.g., tropical latitudes) are already closer to their physiological limitations, and are therefore at greater risk of exceeding temperature thresholds as temperatures rise (Gourdji et al. 2013, Teixeira et al. 2013). African corn yields decrease each day with temperatures above 30 °C, yields decreased by 1% under optimal moisture conditions and by 1.7% under drought conditions (Lobell et al. 2011). Warming leads to higher moisture losses from soils, exacerbating drought conditions and limiting growth in water-limited regions (Sheffield and Wood 2012).

Increased temperatures have led to an earlier start to, and lengthening of, the global growing season. The growing season increased by 10–20 days on average around the world over the 20th century (Linderholm

2006, Körner and Basler 2010, Sheffield and Wood 2012). Longer growing seasons can increase yields and allow for double-cropping, particularly in temperate latitudes, provided that sufficient water and nutrients to support additional growth are available, and provided that higher temperatures do not interfere with a crop's cold-temperature requirements for germination (vernalization; Sinclair 1992) or exceed physiological limitations. Warmer temperatures also increase rates of decomposition and may lead to greater soil-nutrient availability, which can, in turn, increase yields (Melillo et al. 1993, Kirschbaum 2004). Higher temperatures can shorten the time necessary for crop development, but in doing so, may prevent the completion of seed fill and, perversely, diminish yields (Harrison et al. 2011, Walthall et al. 2012). Early senescence (end of growing season), triggered by extremely warm temperatures (greater than 34 °C) poses a documented risk to tropical wheat harvests, for example (Lobell et al. 2012).

In some regions, however, higher temperatures lead to a shortening of the growing season and to reduced yields as physiological temperature or moisture thresholds are breached (Ericksen et al. 2011). In semiarid zones where temperature and moisture are already approaching biophysical thresholds, increasing temperature stress, an increasing number of dry days, highly variable seasonal rainfall, and increasing rainfall intensity are expected to lead to growing-season declines that are important to food-security outcomes (Ericksen et al. 2011). This is particularly true in developing regions where local and regional production have a major bearing on food availability.

Changing precipitation patterns and variability influence production and have been demonstrably influential in many corn-, soy-, rice-, and wheat-producing regions around the world (Lobell et al. 2011, Fallon and Betts 2010). In 2012, for example, the midwestern United States suffered a 13% drop in corn yields following an extremely hot summer coupled with severe drought (USDA NASS 2013). In both 2008 and 2013, severe flooding delayed corn planting in some areas of the midwestern United States and drowned already-planted crops (LeComte 2014). A shift to drier weather, together with expanded land area, in the summer of 2013 in the same region led to record-high U.S. corn production that year (USDA NASS 2009, 2014). In regions experiencing more rainfall, or more-intense rainfall events, increased rates of erosion lead to losses of organic carbon and nutrients in soil (Walthall et al. 2012). The net influence of such precipitation changes depends on a variety of soil characteristics, physiological crop characteristics, and the response



of soil microbe communities (Nearing et al. 2005). Rates of erosion, however, appear to increase disproportionately with annual average rainfall by a ratio of approximately 1.7, indicating that the effects of soil erosion are likely to be important in affected regions (Nearing et al. 2005).

Changes in reliable crop-growing days, more-variable seasonal rainfall, temperature stress, and more dry days during the growing period increase instabilities in crop-production systems (Ericksen et al. 2011). As the climate-driven growth factors for crops (e.g., temperature, precipitation, pests, disease, extreme events) shift, the stability of production is likely to become more unpredictable over time and across geographical regions.

Elevated atmospheric CO₂ concentrations allow plants to keep their stomata closed for longer periods while still gaining sufficient CO₂ for photosynthesis, which results in improved water-use efficiency (Kirschbaum 2004). Elevated atmospheric CO₂ concentrations can also increase the levels of plant residue entering soils, increasing soil organic matter (van de Geijn and van Veen 1993), though this effect is mediated by increased soil-erosion rates brought on by more-intense precipitation in some regions, and more generally by diminished nutrient levels in plant tissues (Walthall et al. 2012).

Temperature, precipitation, and atmospheric CO₂ together interact to affect production by means additional to their individual effects described above. Higher average temperatures associated with longer growing seasons increase rates of evaporation and evapotranspiration, diminishing soil-moisture stores and increasing crop-moisture stress (Kirschbaum 2004, Trenberth 2011), even in regions where precipitation remains unchanged. The most severe droughts typically result from a combination of rainfall deficits and abnormally warm temperatures (Trenberth 2011); droughts occurring in a warmer climate are of a greater intensity (Trenberth et al. 2014). Of course, not all droughts are induced by climate change (Porter et al. 2014, Dole et al. 2011, Hoerling et al. 2014), as history demonstrates. However, climate change does appear to increase the probability of heat waves associated with drought events across much of the globe (Otto et al. 2012, Knutson et al. 2013, Diffenbaugh and Scherer 2013), perhaps by a factor of four (Otto et al. 2012, Rahmstorf and Coumou 2011, Knutson et al. 2013, Diffenbaugh and Scherer 2013). In East Africa, for example, the drought of 2011 (Funk 2012, Lott et al. 2013) and the low precipitation levels of 2012 (Funk et al. 2013) have been linked to changes in climate.

In addition to the direct physical effects, climate influences the range and infestation intensity of crop pests and pathogens.



These changing parameters directly affect crop yields. Individually, each has a range of possible effects on a crop. Together, the possible combinations mean that potential outcomes are highly specific and depend upon the relative balance of the changes being experienced within localized conditions.

In addition to having direct physical effects on food production, climate influences the range and infestation intensity of crop pests and pathogens. Many bacterial and fungal pathogens affecting staple, specialty, cash, and non-food crops are associated with climate variables (Anderson et al. 2004). Crop-eating insects, some of which are also disease vectors, also respond to changes in climate (Bale et al. 2002, Thomson et al. 2010). Milder winters, more and more-damaging severe-weather events, higher nighttime and overall temperatures, and increased humidity enable pest and pathogen growth, survival, and spread; extremes in drought and precipitation stress in plants make crops more susceptible to pathogens (Bale et al. 2002, Harvell et al. 2002, Kirschbaum 2004, Elad and Pertot 2014, Irely et al. 2006, Gregory et al. 2009). Weather is the primary driver of the emergence of 25% of crop-pathogen species; shifts in weather caused by climate change are therefore very likely to affect pathogen dynamics (Anderson et al. 2004), potentially reducing yields.

Production changes resulting from changes in underlying climatic conditions can also interact with stressors such as conflict, market stresses, or non-climate-related disaster conditions to alter the

stability of food availability (Davis 2002, Watts 1983). In the 2011 Horn of Africa famine, for example, multiple lower-than-average rainy seasons diminished crop harvests and available forage in Ethiopia, Kenya, and Somalia. However, famine was declared in only one of those countries (Somalia), where a militant group interfered with attempts to deliver adequate relief (Hillbruner and Moloney 2012, Lautze et al. 2012, Maxwell and Fitzpatrick 2012, Menkhaus 2012). As a consequence of the induced scarcity, the number of people selling household assets in Somalia greatly outnumbered buyers, so that the assets were not effective sources of income—income that could have facilitated access to food through purchase rather than by direct production (Maxwell 1996, Watts 1983). When sold assets include livestock or other means of production, future food-production capacity is reduced, which can lead to diminished food-security outcomes long after the transitory initial cause has passed (Lybbert et al. 2004).

Estimates suggest that 30%–50% of total food production is lost globally as waste (Gustavsson et al. 2011). Similar levels of waste are observed in developed and developing nations, with differing causes in each case. As climate change increasingly influences the processing, packaging, storage, transportation, and trade of food, rates of food waste may increase in developing countries, where technological limitations prevent crops from being harvested quickly enough to avoid spoilage or to be managed properly afterward (Godfray and Beddington et al. 2010), potentially influencing food availability. In developed nations, such pre-retail losses are less significant; the issue is more one of utilization, and is discussed more fully in the “Food Utilization and Stability” chapter of this report.

5.1.1.2 Livestock Production

Livestock operations occur over approximately 30% of the Earth’s ice-free land surface. Livestock operations provide a livelihood for over a billion people, including 600 million households in less developed areas (Thornton 2010).

Livestock operations may include cattle, dairy, swine, and/or poultry and may be part of farm operations that also grow crops (“mixed” systems). Mixed agricultural systems are common in low- to middle-income countries, where animals are commonly raised outdoors and fed with crops grown on-site, with forage, or a combination of the two (Sutherst 2001, Naylor et al. 2005). Livestock may also be raised separately, either indoors and fed with crops grown elsewhere (e.g., poultry houses) or outdoors on forage (i.e., grazing systems).

The livestock industry contributes over USD 1 trillion annually to the global economy (Thornton 2010). Since the late 1990s, livestock has grown more rapidly than other agricultural sectors and currently represents 33% of the GDP of developing countries (Thornton 2010). This growth is associated with urbanization and income growth in developing regions (Delgado 2005). In places like East Asia, poultry and swine production have expanded rapidly. The livestock sector plays an important role in agricultural systems and is a critical source of protein and micronutrients; however, comparatively little systematic assessment has been done relative to non-animal-based agriculture (Porter et al. 2014).

Risks to livestock systems are substantial and concern livelihoods, the provision of safe and nutritious food, and food security (Thornton et al. 2009, Walthall et al. 2012, McCarl et al. 2014). These risks, along with the increasing demand for animal-sourced foods worldwide, may lead to increased pressure on ecosystem services and natural capital of production areas (Herrero and Thornton 2013).

Heat stress from higher temperatures diminishes food intake and physical activity for livestock, leading to lower growth, survival, and reproductive rates, as well as lower production of meat, milk, and eggs (Nardone et al. 2010, Walthall et al. 2012, West 2003), though physiological acclimatization is possible to some extent over time (Kadzere et al. 2002, Saxena and Krishnaswamy 2012). Increasing temperatures require greater water intake; *Bos indicus* cattle, for example, require 3 kg of water per kilogram of dry-matter feed at 10 °C, but 10 kg of water per kilogram of dry-matter feed at 35 °C (Thornton et al. 2007). Indoor livestock (primarily poultry and swine operations in developed countries) face increased heat stress and associated mortality in a changing climate, absent adaptive measures to manage higher air temperatures (Turnpenny et al. 2001).

Climate change also affects livestock indirectly through disease and pests, quality and quantity of pasture and forage crops, and feed-grain production (Rötter and van de Geijn 1999, West 2003, White et al. 2003, Thornton et al. 2009, Nardone et al. 2010). Temperature increases and precipitation shifts may accelerate the development of certain livestock pathogens and parasites, along with distribution of their vectors, exposing livestock to novel pathogens (Harvell et al. 2002, Thornton et al. 2009, Pérez de León et al. 2012). At the same time, heat stress can weaken immune function in livestock. Together, these factors could require an increase in the use of veterinary medications (Nardone et al. 2010, Tirado et al. 2010).



Precipitation changes and warmer temperatures can lead to more forage for grazing livestock (Hanson et al. 1993). Changes in climate and atmospheric composition can also result in decreased forage-nutrient content and digestibility, and consequently, poorer livestock performance (Hanson et al. 1993, Klein et al. 2007, Baker et al. 1993, Tubiello et al. 2007, Thornton et al. 2009). The effects of climate on these indirect factors for outdoor livestock production are ecosystem-specific (Baker et al. 1993) and vary by location and operation type.

5.1.1.3 Fishery Production

Capture fisheries and aquaculture provide 3 billion people with almost 20% of their average per-capita intake of animal protein, with an additional 1.3 billion people obtaining 15% of their protein from this source (HLPE 2014). In some regions (e.g., West Africa, Cambodia, Bangladesh, Indonesia, Sri Lanka), fish make up over 50% of all protein consumed, making fish a highly important source of nutrition in food-insecure regions (FAO 2012b). 90%

of fishers depend on small-scale capture fisheries; many of these people are food insecure (HLPE 2014).

Fisheries are dynamic social-ecological systems affected by many non-climate stressors that are particularly important for food security, including rapid market changes, exploitation, and governance (Daw et al. 2009). The combined effects of competition for resources, pollution, overfishing, habitat modification, acidification, temperature, and climate-driven changes on small-scale fisheries and aquaculture in these regions are likely to be damaging to fishery health and sustainability, resulting in decreased incomes for fishing families (affecting food *access*) and overall reductions in food availability for fishing communities (HLPE 2014). Current methods of analysis cannot distinguish the relative importance of each influence upon fishery health (IPCC 2014).

Climate-driven changes in water temperature, salinity, and dissolved-oxygen content affect the physiology and behavior of wild fisheries species, as well as that of their predator and prey species, affecting population dynamics and distribution (Walther et al. 2002, Roessig et al. 2004, Brander 2007, Brander 2010, Ottersen et al. 2001). Warmer weather caused by El Niño offers a glimpse into the potential effects of warmer weather on fisheries (Mysak 1986, Fromentin and Planque 1996, Weststad et al. 2000). An increase in warmer-water fish species in response to higher water temperatures is observed at higher latitudes, and decreases in subtropical species have been observed in the tropics (IPCC 2014, Cochrane et al. 2009). Short-term changes in fish species type and population size result in changes in fishing opportunities, operational costs, and sales prices, with increased risks of damage or loss of infrastructure and housing for communities relying on marine resources (FAO 2008b). El Niño/La Niña events themselves may also be influenced by climate change (McGowan et al. 1998), making the changes described above more probable in the future as a result of more frequent oscillations.

Climate change has been linked to permanent shifts in the distribution of fish species in wild fisheries. For example, over a span of 25 years, Perry et al. (2005) found that of 36 species of North Sea deep-water fish, 21 had shifted their centers of distribution northward or to deeper waters to follow colder water. Temperature increases also affect the food sources of fisheries species by increasing productivity in cooler regions and decreasing productivity in warmer regions (Richardson and Schoeman 2004). Such



changes diminish food availability and access for the 90% of capture fishers who are employed by small-scale fisheries (FAO 2012b). Aquaculture allows for a greater degree of control over growth conditions than capture operations in wild fisheries, but nonetheless remains vulnerable to climate pressures, including shifts in water temperature and chemistry, water availability, disease prevalence, damage from extreme events and sea-level rise, and changes in fishmeal availability as feed from capture fisheries (Brander 2007).

Elevated atmospheric CO₂ leads to higher levels of acidity in both wild and cultured fisheries. Higher acidity prevents the formation of calcium carbonate shells and skeletons in important fisheries species and their predators, leading to population declines with continued acidification (Cooley and Doney 2009).

5.1.1.4 Wild Game

Wild game is the primary source of meat and income for hundreds of millions of people in developing countries (Milner-Gulland and Bennett 2003). For the poorest households, wild game is a traditional safety net that protects impoverished rural households from chronic malnutrition during times of scarcity (Golden et al. 2011, Myers et al. 2013), including when livelihoods collapse and income sources disappear (Milner-Gulland and Bennett 2003). Wild game is consumed in rural areas by the poor and food-insecure, as well as in urban areas where it is obtained through trade by higher-income households (Brashares et al. 2011).

In addition to facing similar physiological pressures as those experienced by livestock, including the influence of high temperatures on meat, milk, and egg production; immune function; mortality; and reproductive rates, wild game is additionally subject to the effects of climate change on its food sources. Climate change affects the growth and seasonality of wild plants that serve as food for wild game, which influences the growth, survival, and timing of important life cycle events (e.g., reproduction) for those species (Ogutu et al. 2014, Kerby et al. 2012).

Much research to date has focused on game species in the Arctic, which is experiencing some of the most rapid and severe climate change on Earth and is home to a large community of subsistence hunters (Arctic Climate Impact Assessment 2004). In Greenland, for example, earlier spring warming has led to a mismatch between forage availability and caribou herds' arrival on their calving range, leading to higher offspring mortality (Post and Forchhammer 2008). Inuit communities that rely heavily on caribou as a food source have also observed changes in

caribou migration patterns, body condition, and meat quality associated with changes in the Arctic climate (Wesche and Chan 2010).

Pests and diseases of wild game species are spreading into new areas as regions experience milder winters (Kutz et al. 2009). For example, unseasonably warm winters in the northeastern United States are correlated with high tick loads that increase moose calf and cow mortality (Musante et al. 2010). It is likely that the effect of climate change on insect populations and parasite loads will extend to other important game species as temperate regions warm, allowing vector-borne diseases transmitted by ticks, midges, and mosquitoes to change in abundance, distribution, and infectivity (Harvell et al. 2002, Altizer et al. 2013).

5.1.1.5 The Natural-Resource Base and Food Production

Food production—agricultural, pastoral, aquatic, and wild—requires a wide range of functioning ecosystem characteristics and processes, particularly those related to soil and water resources (Power 2010). Changes in these characteristics and processes can occur through management, climate change, or numerous other activities and events. In developing regions, production systems are already challenged by current levels of natural-resource degradation combined with a lack of investment in infrastructure and technology (Nardone et al. 2010). In these cases, where there is adequate technological capacity, one or more of the natural constraints to production may be offset through management interventions such as irrigation, fertilizer application, or enhanced biological resources through selective breeding and use of improved varieties (Keeney and Hatfield 2008, Power 2010).

At the other end of the spectrum, indigenous and other communities that have close cultural and geographical ties to traditional or wild-food production systems are affected by changes in the natural-resource base. Shifts resulting from climate change affect the range and distribution of traditional food sources, leading to changes in food availability and the cultural appropriateness of available foods (i.e., food *utilization*; Lynn et al. 2013). Land management and administrative restrictions can hamper the harvest and production of food sources following geographical shifts in where food sources are available (Dougill et al. 2010).

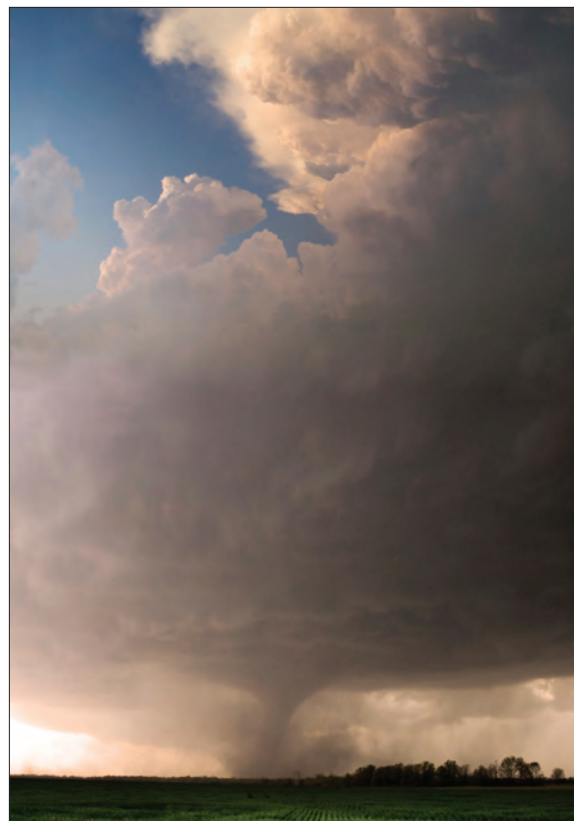
Soils provide a substrate and nutrients for plant growth, while mediating water supply and quality; their health is therefore paramount to the underlying ability of ecosystems to produce food (Walthall et



al. 2012). A soil's nutrient levels, organic matter content, physical structure and depth, pH, microbial community, and contaminant load determine its productive capacity (Brady and Weil 2008). Each is subject to alteration through changing climatic conditions and management practices. Changing temperatures and precipitation patterns alter nutrient turnover rates and consequent plant availability. The level of organic matter in soil affects the provision of water to crops. Soil rich in organic matter better holds water and can provide more water to growing crops during drought conditions than soils low in organic matter (FAO 2005) and influences microbial dynamics and nutrient availability. More-intense rainfall events can erode and alter the physical structure and depth of soils, as well as reduce organic-matter concentrations (Walthall et al. 2012). Intensification of agricultural practices may further exacerbate these effects by affecting soil compaction, levels of soil organic matter and nutrients returned to soils, and the concentration of salts and other chemical constituents (Power 2010, Huang et al. 2011, Montgomery 2007).

The water cycle is also affected by climate change (IPCC 2007b, Haddeland et al. 2014, Rudorff et al. 2014, Barnett and Pierce 2009, Immerzeel et al. 2010, Elliott et al. 2014). Livestock systems are conditioned to respond to seasonally available moisture from precipitation, springs, or groundwater aquifers, or through management of water resources through various well and reservoir developments, and therefore respond to water-cycle changes. Seasonal availability of water may be affected by temperature trends that influence snowmelt timing and rapidity, as well as changes in the timing, amount, seasonality, type, and intensity of precipitation. Precipitation effects may be exacerbated by higher temperatures that increase moisture losses through evaporation and transpiration (Jiménez Cisneros et al. 2014).

Regions that use melting snow to supply water to growing crops are vulnerable to climate change as higher temperatures induce earlier peak flow, which leads to reduced water availability in summer and fall. In this situation, irrigation can help to regulate water supply where the necessary reservoir infrastructure exists, though such infrastructure is not without limitations. Irrigated Asian rice systems, for example, have experienced increased salinity in the soil and in irrigation water (Wassmann et al. 2009). Elliott et al. (2014) conclude that even where adequate irrigation-water supplies exist, they may be unable to offset greater warmth when combined with reduced precipitation. Changes in underlying conditions and the "natural" state of surrounding



ecosystems therefore influence food production, even with adaptation (Zhang et al. 2007).

One review of 160 studies on the food-security benefits of soils and land management concluded that (1) land management that includes improved management of soil organic-matter, appropriate nutrient inputs in both time and space, and methods for reducing pests and diseases generally leads to increased yields, although the magnitude and variability of results varied by specific practice and agro-climatic conditions; (2) isolating the yield effects of individual practices is complicated by the adoption of combinations or "packages" of sustainable land-management options; (3) sustainable land-management generally increases soil carbon sequestration; and (4) rainfall distribution is a key determinant of the mitigation effects of adopting specific sustainable land-management practices (Branca et al. 2013).

Another study found that the effects of climate change on water availability and food security differ substantially among five important South Asian hydrological basins upon which 1.4 million people depend (Immerzeel et al. 2010). The study estimates that the food security of 60 million people dependent on these basins, particularly those dependent on the Brahmaputra and Indus, are susceptible to anticipated hydrological changes.



Agricultural production depends on soil properties and the availability of water, among other natural resources (Porter et al. 2014). Production systems are managed to alleviate stresses due to soil degradation, reduced soil fertility, pests and disease, and impaired water resources in order to enhance crop and animal sources of production. Land and water resources have been developed over centuries to meet regional and local needs (Vandermeer and Perfecto 2012). With the “green revolution” of the mid-20th century, agricultural production has been enhanced through technological advances (Pingali 2012). However, competition for land and water resources is emerging as a consequence of population growth (Lambin and Meyfroidt 2011, CNA Military Advisory Board 2014); climate change will affect production systems in ways that may exacerbate this competition (Porter et al. 2014, Hatfield et al. 2014). Intensifying agricultural production given available land and water resources, while managing multiple demands and reducing damage to the natural resource base, will be more challenging in a changing climate (Tschakert et al. 2008, Ojima et al. 2009, CNA Military Advisory Board 2014).

5.1.2 Processing, Packaging, and Storing Food

Processing, packaging, and storing are frequently prerequisites for food to reach its ultimate consumers. These activities are present in many food systems, enabling the provision of fresh and safe food to consumers who may be distant from agricultural areas. Food supply chains are becoming increasingly globalized, with retailers engaging with smallholders (farms with fewer than 2 ha) across countries and income levels (Lee et al. 2012).

Food processing preserves and adds value to agricultural products (Simon and Thirion 2013). There are two general categories of food processing: primary and secondary. Primary processing includes actions such as cooling to extend shelf life, and milling. Secondary processing makes agricultural products more readily edible. Secondary processing can also add significant economic value to harvested goods (Meléndez Arjona and Uribe 2012), for example, by creating bread from wheat (FAO 2004), corn meal from corn (Simon and Thirion 2013), oils from tree crops (Poku 2002), tomato sauce from raw tomatoes (Issahaku 2012), and hot sauce from peppers (Meléndez and Uribe 2012).

Food processing is directly sensitive to climate and must be suited to local conditions, as changing temperatures and moisture levels have different effects on foods depending on where they have been produced (Halford et al. 2015). An example is the

cooling of fruits and vegetables following harvest to extend shelf life (Kurlansky 2012). Active cooling methods require considerable amounts of energy—more so with higher temperatures (Thompson 2002), which entail higher energy costs and raise consumer prices (Moretti et al. 2010). Increasing temperatures can in this way lead to strains on electricity grids that extend beyond the food system (FAO 2008d, Vermeulen and Campbell et al. 2012). Food systems with minimal packaging and processing, or with inadequate cold-chain continuity, are inherently more vulnerable to rising temperatures than those that respond to changing conditions by adapting food packaging (Lee et al. 2012, James and James 2010, Dangour et al. 2012).

Climate change may also affect the location of food-processing and packaging facilities, which are often located near the original food-production site for cost, convenience, and regulatory reasons (FDA 2006). As production shifts to reflect changes in climate, the location of processing facilities will also need to move (Hatfield et al. 2014). For example, growing corn in regions where it historically has not been cultivated requires the construction or expansion of nearby processing and transport facilities in order to handle the increased bulk (Petroliia 2008).

The effects of climate change on food processing are a function of multiple choices being made simultaneously among different actors within the food system, determined by the rapidity of climate change, structural changes within the food system, and changes in consumptive demands. From 1961 to 2007, global average per-capita food consumption increased from 2,250 kcal per person per day to 2,750 kcal per person per day; the biggest caloric increases were in the categories of cereals, vegetable oils, and animal products (Kastner et al. 2012). Changing dietary composition is also important and may become more important than population growth as a driver of agricultural expansion and trade in the near future (Kastner et al. 2012). Urban consumers in West Africa, for example, increasingly demand processed foods that are ready to use, are nonperishable, and do not require a great deal of preparation (Simon and Thirion 2013). These foods are often imported, and the lack of domestic supply has led to transitory supply shortages and influenced prices, which in turn results in declines in food intake and higher rates of food insecurity (Becquey et al. 2012).

Corporations are beginning to recognize the risk that climate change poses to supply chains and how that risk varies based on regulatory environment, energy prices, and temperature regime (CDP 2015). Packaging and logistics companies in some countries



now collaborate with farmers and organizations that seek to reduce food waste at different stages of the food system to develop packaging that provides ventilation and temperature control, and enables flexible bulk transport to retail outlets (Verghese et al. 2013). New ways to monitor foods with sensors and electronic tagging to communicate harvest dates and to notify retailers when spoilage occurs are under development (Deloitte 2013).

5.1.3 Trading and Transporting Food

Following production, food is sold to off-farm interests and ultimately to consumers. The role of food trade has been growing. For instance, Japan now relies on imports to meet 75% of its annual cereal-consumption needs, compared to 26% in 1961 (USDA 2015). In this way, trade influences food availability. Global cereal and meat exports have climbed 27-fold since 1961 and are now worth approximately USD 192 billion a year, or 8%–10% of the total value of global production (Figure 5.2). Global trade linkages can provide consumers with access to non-local foods, while providing producers a means to earn money through geographically far-reaching trade networks (Bellemare 2012).

Food is transported primarily by international waters and rail (29% each), followed by truck transport

(28%), and inland waters (10%; Weber and Matthews 2008). Cereals/carbohydrates comprise the greatest proportion of freight (14%), followed by red meat (10%), with nonalcoholic beverages, fats/sweets/condiments, non-red meat proteins, and processed food each responsible for about 6%–8% (Weber and Matthews 2008).

Transportation is an intermediate activity linking each food system activity. Multiple climate variables can influence transportation systems and the foods they carry. Transportation is particularly sensitive to extreme-weather events through damages to infrastructure, such as flooding and storm surge. While immediate effects on the transportation system may be temporary, disruptions can affect food availability and food safety, and impair just-in-time food-distribution networks (Wu and Olson 2008, Koetse and Rietveld 2009). Heat waves stress transport systems, as food needs to be moved faster and/or the cold chain needs to be strengthened to avoid spoilage.

Extreme weather can influence food transport in vulnerable locations (e.g., along coastlines, near rivers), particularly when maintenance has not taken changes in climate into consideration (Mashayekh et al. 2012). Vessels using inland waterways must reduce the weight of cargo that they carry when

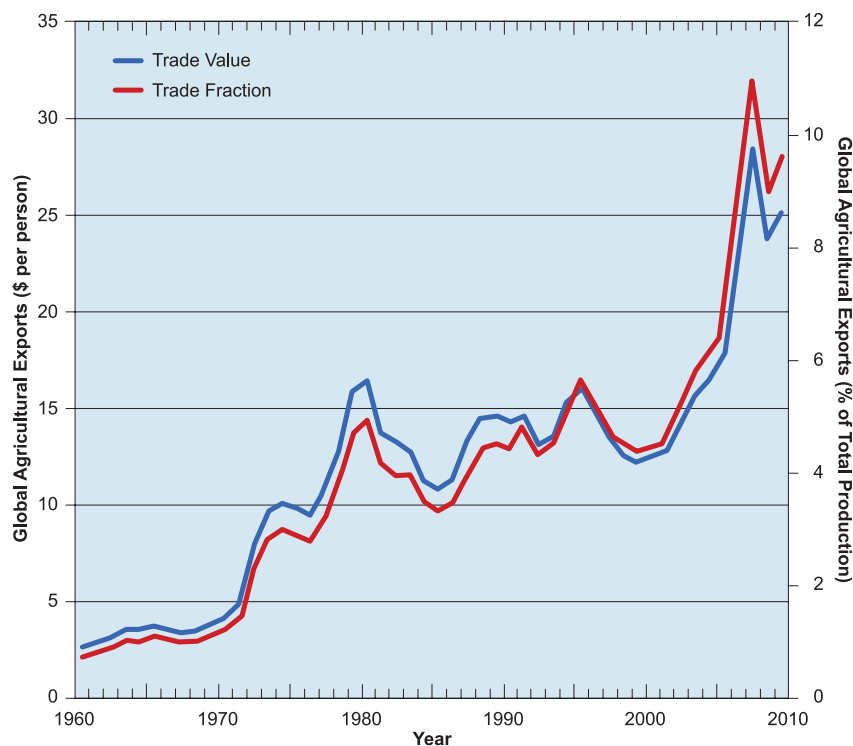


Figure 5.2 Historical trend in global per-capita cereal and meat exports. Global per-capita cereal and meat exports have increased as a proportion of total production since 1961, reflecting the increased relevance of trade to food availability and stability. Source: FAO 2014d.

water levels in rivers and lakes are low, leading to an increase in shipping costs and the number of trips they must make (Attavanich et al. 2013, Jonkeren et al. 2014, Millerd 2005 and 2011). Storm surge, river floods, and extreme weather affect food transportation and supply-chain integrity through effects on sea ports (Becker et al. 2013, Blake et al. 2013). For perishable foods, lack of a cold chain or refrigerated transport can result in large losses due to spoilage, particularly under higher temperatures (Choudhury 2006, Mittal 2007). Intense precipitation increases accident frequency in land transport and decreases traffic speed (Maze et al. 2006, Brijs et al. 2008). Heavy rains lead to flooding of transportation infrastructure (e.g., roads, railways) and mudslides that can interfere with continued food availability (McGuirk et al. 2009).

Regional and national disparities in production, whether chronic or generated by shocks, have resulted in an increasing trend, particularly in less-developed nations, to adopt international trade for overcoming food deficits (Jafry 2012). When an area experiences a food shortage, prices rise. This shortage attracts food from areas of surplus production, helping to improve food availability in the area of the shortfall (OECD 2013). Consumers benefit from increases in trade through a greater variety of foods, increased competition, and lower prices. Trade benefits agricultural producers as well by supporting their income through sales of surplus production and by improving productivity by providing lower-priced or more-varied production inputs, such as seed, fertilizer, pesticides, and machinery (Hebebrand and Wedding 2010, OECD 2013). On a broader scale, trade also helps generate economic growth, boosting households' income and their means to purchase food, while enabling countries to earn foreign exchange for food imports (Schiavone 2010, Cline 2004).

However, such a highly linked system also means that distant events, including climate and weather events like heat waves and droughts, can generate local food shocks that are far removed from the site of the original disturbance (Abbott and Battisti 2011). Rapid urbanization compounds this possibility, as millions of people have become more dependent on markets for their primary food supplies (Berazneva and Lee 2013, Porkka et al. 2013). Flooding and temperature extremes (IPCC 2012) are examples of climate and weather influencing the stability of food *availability* by hindering the movement of food from its place of production to consumers, by altering food prices in response to changes in the price of transportation (*access*), and by increasing the likelihood of food contamination (*utilization*).

The linkage between climate change and trade is indirect. When adverse climate reduces production of an agricultural commodity, prices for that commodity can increase, leading governments to sometimes adopt restrictive measures on trade (Schiavone 2010, World Bank 2008a). Disruptions in regional and international markets can result, leading to further price increases. These consequences may also spread to other commodities for which production remains unaltered, due to spillover effects (Zhao and Goodwin 2011, Slayton 2009). An example of this is the 2008 food price crisis, in which world rice price tripled in four months primarily as a result of trade restrictions imposed by some of the largest rice-exporting countries in reaction to rising prices of other commodities, during a time of record rice production and ample stocks (Slayton 2009). In Burkina Faso in 2008, high food costs, due in part to global price increases, led to protests and riots in a number of regions, despite above-average domestic agricultural production that year (FAOSTAT 2015a, Bush 2009). This is an example of the issue of scale when managing food security: it is not a matter of simply considering multiple scales, but of considering all scales, from the local to the global, at once. The Burkina Faso example demonstrates that global food prices can affect food costs in countries even without significant food imports (Aker et al. 2010, Haggblade 2013). The Burkina Faso situation could not have been predicted based upon local conditions or choices; knowing what was happening globally was necessary in order to properly interpret those events.

5.2 Adaptation for Food Availability and Stability

Adaptation in this report refers to actions that lead to “mean reductions in risk and vulnerability by the adjustment of practices, processes, and capital in response to the actuality or threat of climate change” (Porter et al. 2014).

Adaptive capacity is mediated by a broad set of socioeconomic drivers (Morton 2007). It is limited by the physiology of crops and livestock, research and development, technology adoption, the ability to convey timely and appropriate information to stakeholders, and social issues (Kane and Yohe 2000, Kates 2000). These factors suggest a wide variety of potential strategies to respond to changes in climate, including insurance, engineering responses, land-use allocation changes, management and policy responses, and research and development solutions (Kandlikar and Risbey 2000). Depending on income

Storm surge, river floods, and extreme weather affect food transportation and supply chain integrity through effects on sea ports.



level and access to resources through government and institutional supports, individual actors in the food system may respond to different drivers and prioritize different actions, with climate being just one of many challenges needing to be overcome at a particular time (Risbey et al. 1999).

Factors affecting on-farm adaptive capacity under climate change include access to varietal traits that thrive in changing environmental conditions, soil characteristics that improve water retention and storage, access to water for irrigation, and information (Porter et al. 2014). Producers invest in new agronomic practices and genetic resources with the goal of buffering detrimental climate effects or taking advantage of changes to remain profitable (Zilberman et al. 2004, Kurukulasuriya and Mendelsohn 2008, Crane et al. 2011). Indicators that specific elements of the food system are not adequately adapting to climate and other stressors (Lemos et al. 2013, Zhu et al. 2013) include soil degradation, falling productivity, and movement beyond ecosystem thresholds that alter functionality (Le Houerou 2002, Moseley 2003, Wessels et al. 2004, Berry et al. 2009).

Constraints in one component of food security may often be compensated through another—e.g., food insecurity may be avoided when production decreases (*availability*) are substituted with food acquired through purchase (*access*). Alternatively, constrictions at one point within the food system may be so severe, or have no feasible alternative possibilities within a local context, that food security may be compromised—e.g., a country with ample food production but inadequate transport conduits has more-limited capacity for food purchases by remote populations. As a consequence of these interactions and dependencies, a systems-based approach is needed to understand the implications of climate change.

Challenges to food availability and its stability have already been observed as a result of climate variability and change—food production, processing, packaging, storage, transport, and trade can all be affected by changes in temperature and precipitation (Vermeulen and Aggarwal et al. 2012). Food-system actors participate within specific environments, using specific tools and crop or livestock varieties suited to a particular environment and available within their means. Because production systems are “optimized” in this way, changes in the surrounding circumstances will require adaptation and altered management practices. As climate change accelerates, greater challenges are expected in responding to changing patterns of yield and productivity, production

costs, and resource availability to ensure sufficient food availability (Walthall et al. 2012). The food system will require significant investment to adapt crop-production technologies or apply these technologies in new places (Malcolm et al. 2012). Similar challenges are expected for other elements of the food system that support food availability—processing, packaging, storage, transportation, and trade (Ericksen 2008).

Farmers have already adopted practices and strategies to reduce the damaging effects of drought, floods, high temperatures, and other phenomena related to climate change on food production (Malcolm et al. 2012). Farmers also have significant technical flexibility to adapt to changes in local weather, resource conditions, and price signals by adjusting crop types, locations, rotations, structural modifications, and management practices (FAO 2011b). That said, the existence of technical fixes to maintain or improve food availability under changing conditions is not a guarantee of their use, since use may be limited due to lack of knowledge of a technology, social constraints to its application, or financial limitations that prevent a producer or other food-system actor from obtaining or maintaining it (Kane and Yohe 2000, Kates 2000, Affholder et al. 2013).

The “yield gap” refers to the difference in crop yields obtained from capital-intensive agricultural systems in the developed world and labor-intensive agricultural systems in the developing world (FAO 2011b). Adaptation holds considerable promise for minimizing yield decreases from changes in climate and increasing yields in regions that currently produce only a fraction of potential yields (Nin-Pratt et al. 2011). Valdivia et al. (2012) and Claessens et al. (2012) demonstrate in two regions in Kenya that the use of new crop varieties and intensive agricultural systems could raise overall productivity and ameliorate climate change through higher yields, even in a high-emissions scenario. There is considerable potential for similar types of improvements using existing technologies (Funk and Brown 2009).

Smallholders represent 85% of all farms in food-insecure nations, of which 87% are located in Asia (Nagayets 2005, FAO 2013a). Smallholder farmers, in addition to the landless and urban poor, are one of the most disadvantaged and vulnerable groups, with the least ability to respond to climate change and severe weather events through investment in new crops, insurance mechanisms, and inputs to maintain production (IFAD 2001, Majid 2004). Investments in agricultural research, a wider



adoption of new technologies, and policy reforms can lead to improved production; support for these innovations remains generally low in many areas where smallholders are predominant (Fuglie and Rada 2013).

Geographic shifts in production areas are expected as a result of climate change (Lobell et al. 2008). It is not necessarily the case, though, that production increases in some regions (e.g., northern latitudes) can fully compensate for production decreases elsewhere (e.g., tropical latitudes; Funk and Brown 2009, Gourdj et al. 2013).

Maintaining a diversity of crop varieties can be one adaptive approach to managing shifts in the underlying environmental conditions of food production. Successful breeding enabled the rapid expansion of hard red winter wheat across substantial climatic gradients—hot, dry, and cold—in North America during the 20th century (Easterling et al. 2004). Unexploited germplasm can continue to push environmental margins for maize production (Easterling et al. 2004, Carena 2013); for example, much research has focused on improving drought and salt tolerance in food crops (Parida and Das 2005). Attempts are underway to collect and protect the genetic diversity of a portfolio of plants that have the characteristics required to adapt food crops to climate change (Dempewolf et al. 2014). Such gene banks are critical to the success of future breeding aimed at expanding plant abiotic tolerances. In livestock systems, a delicate balance must be preserved between mining the genetic diversity of native species through breeding programs to develop animals that are better suited to meet expected drought and nutrition challenges, while at the same time maximizing feed-conversion efficiencies (Hoffmann 2010).

Genetically modified (GM) organisms may also be used toward these ends, as one of multiple solutions aimed at meeting the world's food needs while managing biodiversity, recreation, and ecosystem services (Godfray and Beddington et al. 2010, Borsari et al. 2014). Commoditized monocropping in much of the globalized food system has resulted in a narrower genetic base for plant and animal production, which may consequently be more susceptible to climate-related threats (Knudsen et al. 2005, Young 2013). Enhancing genetic resources, whether through better use of genomics or genetic modification, is important to increasing on-farm resilience to climate change and weather extremes. A range of strategies including GM organisms, enhanced breeding systems, and multicrop management schemes have the potential to enhance



resilience to changes in climate (Jacobsen et al. 2013, Lin 2011).

Not all adaptive strategies are universally applicable, however. Heat-abatement technologies for livestock are myriad, but costly from infrastructure and energy perspectives. Those costs increase under higher-emissions scenarios (do Amaral et al. 2009, Key et al. 2014). Solar radiation, wind, stocking rate, and design will determine the capacity of a livestock-production operation and its livestock to adapt to weather fluctuations and a changing climate (Cooper et al. 1998). The magnitude of improvements needed will vary geographically, and in some cases improvements will not prevent considerable economic loss or will be cost ineffective. For instance, in the United States, heat abatement is economical for poultry layers, but not for broilers (St-Pierre et al. 2003). The economics of various adaptation strategies for livestock production vary based on the livestock type, location of the operation, and economic circumstances of the situation under consideration. The rapid development of livestock systems in developing countries presents a number of challenges due to a combination of intensified environmental effects and the need for enhanced infrastructure to accommodate the increase in livestock production, especially with swine and poultry (Herrero and Thornton 2013). Recent attention has been focused on developing and implementing sustainable intensification practices



Transportation of food commodities can be highly vulnerable to climate variability and change, but substantial adaptive capacity exists to manage those risks, particularly in developed countries.



associated with expanding animal-sourced products. The demands for maize and soybean as animal feed to support beef and swine production highlight some of the challenges faced by intensification efforts (Herrero et al. 2013, Eshel et al. 2014).

Competition for resources may also diminish adaptive capacity. Competition among different end-users for water resources (e.g., agriculture, urban areas, and industry) likely diminishes available water in regions that depend heavily upon irrigation for crop or livestock production (Elliott et al. 2014). This type of competition reduces adaptive capacity, particularly in arid regions.

Food waste represents an area of much potential improvement for food availability in regions where food spoils before it can be sold or consumed. When food is cultivated and raised in adequate quantities but then lost to spoilage between the farm gate and the market or table, this production is effectively lost to the consumer. In the Southern Hemisphere, rates of loss to spoilage reach as high as 40% of all production for vegetables; losses are lower for grains (Parfitt et al. 2010, Kader 2005). Standards and regulations for food processing and packaging are key ways that large retailers engage with producers as a means to increase food-safety and quality standards in response to elongated food chains (Lee et al. 2012). In labor-intensive food systems, where a short supply chain is more likely, food is traded

with little or no packaging (Lee et al. 2012). Systems with minimal packaging and processing, or that have inadequate cold-chain continuity, are inherently more vulnerable to rising temperatures than those that can respond to changing conditions by adapting food packaging (Lee et al. 2012, James and James 2010). Cooperative investment in infrastructure along with improved support, standards, and sustainability could result in improved food availability by reducing food waste (Parfitt et al. 2010).

Transportation of food commodities can be highly vulnerable to climate variability and change, but substantial adaptive capacity exists to manage those risks, particularly in developed countries. Alternative transportation routes, for example, have at times allowed for compromised or disrupted routes to be bypassed, saving producers who had access to those alternatives from significant financial losses while maintaining food-distribution functions that generate food availability (Changnon 1989). The use of containers in food trade offers significant advantages over other bulk methods by improving loading efficiencies and allowing products to remain untouched from origin to destination, representing a potential adaptation in ports where container ships may dock given changing conditions (O'Reilly 2012).

Maintenance and infrastructure improvement can reduce vulnerability to extreme events (Canning and Bannathan 2000). In some countries, infrastructure has been constructed that allows for storm surge and sea level rise without significant losses or a change in the location of maritime transportation infrastructure (e.g., Love et al. 2010). Adaptation capacity may also be significant in developing nations under some circumstances. In Bangladesh, for example, efforts have been successful to reduce vulnerability to sea level rise (Adger et al. 2007, Rawlani and Sovacool 2011). 63% of 93 global port facilities have at least one policy that specifically addresses potential climate change effects (Becker et al. 2012).

Proper food processing, packaging, and storage can protect food from spoilage. Regulations address appropriate temperature conditions for a food product to minimize spoilage and appropriate packaging to maintain food safety (WHO 2003b). As temperatures increase, the challenges and expenses of food processing, packaging, and storage are expected to increase as well. Refrigeration of food consumes an estimated 15% of global electrical consumption, a figure that may be expected to increase as rising temperatures increase the amount of cooling required to maintain food safety (Coulomb 2008).

Corporations have taken notice of the effects climate change can have on food production and the life of a product from farm to consumer. Their assessments are often given in reports to their shareholders and through other public documents. The J.M. Smucker Company (“Smuckers”), for example, which purchases coffee from 25 million farmers worldwide and is one of the four largest coffee companies globally, announced in 2012 a sustainability plan focused on addressing the challenges of climate change on coffee production and for the underlying ecosystem services that support it (Smuckers 2012). In another example, McDonalds Corporation’s 2012–2013 Corporate Social Responsibility and Sustainability Report, states that it is committed to maintaining safe food temperatures through careful food handling (McDonalds 2014), representing another mechanism for adaptation within the food system.

An emerging issue for food availability involves adaptation at the international scale through the transnational acquisition of land resources. After adverse weather (Headey and Fan 2008), increasing demand, and rising fuel prices combined to rapidly raise food prices around the world in 2008, leading many corporations and governments to acquire property rights in foreign countries (Cotula et al. 2009), in part as a hedge against unfavorable climate conditions in any one region. Such property right transfers have the potential to influence food availability both in the countries selling the land rights and in the purchasing countries (Rulli et al. 2013).

Another means of meeting the challenges to food availability is sustainable intensification (Tilman et al. 2002)—producing more food while minimizing the environmental effects of doing so (Garnett et al. 2013). Sustainable intensification is based on three premises: (1) increased production through (2) higher yields rather than land conversions and (3) long-term environmental sustainability on equal terms with higher productivity. The concept does not specify the techniques to be employed. Under sustainable intensification, diverse approaches, including capital-intensive, labor-intensive conventional, high-tech, agro-ecological, or organic food-production systems, are to be rigorously assessed, with biophysical and social contexts taken into account (Garnett et al. 2013). An example of sustainable intensification is management that promotes long-term increases in soil organic matter and relies on landscape-scale strategies such as rotational diversity, cover crops, and perennialization (Gregorich et al. 2001).

5.3 Measuring Food Availability and Stability

There are two general methodological categories for assessing food availability. One category involves large-scale production and import/export estimates, the balance of which is then scaled to population. This can provide a high-level indicator of food shortages or excesses but cannot identify distributional discrepancies at the subnational scale, and also misses important food-insecurity indicators as a consequence. The second measurement category involves household-level surveying to identify consumption patterns and shortages. These methods better represent food availability at the highly relevant household and community scales, but cannot always account for within-household distributional discrepancies, and tend to underestimate overall consumption. The resource-intensiveness of survey methods limits the ability to maintain continuous records, and samples may not always scale to accurately reflect broader conditions. Each measurement type is discussed in further detail below.

At the national level, food availability includes products from either domestic or foreign sources (i.e., domestic production or imports), as well as any carryover stock from the previous year. Production can be used for food or nonfood purposes, including fuel, fodder, and fiber (Maxwell 1996). Because food availability is composed of many different food-system components acting and reacting simultaneously, the measurement of food availability typically must integrate several different measures.

Remote sensing of yields and production area, including satellite-based observation, is growing for food-production applications (Funk and Budde 2009, Funk and Brown 2009). Estimates of harvested area may use a combination of high- and low-resolution satellite imagery (Marshall et al. 2011, Grace et al. 2012). Modeling based on satellite observations of rainfall, such as the Water Requirement Satisfaction Index, may also be used to generate production estimates (Senay and Verdin 2003, Verdin and Klaver 2002). Much of the satellite data collected are then distributed through programs such as the Famine Early Warning Systems Network (FEWS NET) to developing and low-income countries to anticipate crop failures and food shortages (Brown 2008).

At the national scale, additional information can be provided by low-tech agricultural surveys and area-frame sampling. There has been a recent recognition of the need to strengthen these systems, and the Global Strategy to Improve Agricultural and Rural



Statistics has been developed with participation from international organizations, national governments, and donors (SPARS 2014).

While food production is critical to food availability, how that production is used requires additional consideration in order to have a measure of actual availability. Domestic supply of a given food item is the amount available for consumption once other uses (e.g., animal feed, biofuel production, starch manufacturing, industrial processing, and waste) are subtracted. When divided by the total population, the domestic supply estimates the per-capita food consumption of each food item.

This measure of food supply provides an overall average estimate of per-capita food consumption, but cannot account for distributional effects or variations within a population. To understand differences in availability *within* countries, regions, and even communities, food availability is usually estimated through short-term food-consumption surveys or by looking at food production and food stocks and assuming that the difference between the two represents food consumed (Maxwell 1996). There are several challenges associated with the measurement of food availability within populations. First, the differences observed within a given population, particularly at subnational levels down to the community or household level, are often a product of access limitations rather than availability. Separating the influences of access and availability on food-security outcomes requires site-specific investigation. Further, even the best surveys tend to underestimate consumption and produce estimates that are quite sensitive to survey design (Deaton 1997); this is especially true of household-expenditure surveys (Smith et al. 2014, Godfray and Crute et al. 2010). In contrast to household-expenditure surveys, individual and household food-intake surveys are somewhat more accurate, though they still tend to underreport actual intake (FAO 2003, Frankenberger 1992, Smith et al. 2006, de Weerd et al. 2014). Finally, few countries have reliable estimates of intra-household food waste; this is particularly true of low-income countries (Godfray and Beddington et al. 2010).

The challenges of estimating domestic food availability are important, as estimates of per-capita consumption of calories and nutrients are constructed from these supply estimates. For example, the FAO's Food Balance Sheets (FAO 2001) estimate the per-capita supply of dietary energy, protein, and fat provided by each food item and by all food items combined. Measuring food supply in terms of energy (calories) and focusing



the analysis on staple foods such as coarse grains rather than documenting nutritional composition and adequacy of food is common. However, particularly as incomes grow, dietary composition shifts from coarser grains toward finer grains or from finer grains toward other items such as meat, fish, and dairy (Bennett 1941, Becquey et al. 2012, Popkin 1998, Drewnowski and Popkin 1997). Consequently, the FAO's Food Balance Sheets become increasingly uninformative as populations become more affluent.

One-sixth of total global agricultural production is traded internationally (Anderson 2010), making trade an important contributor to food availability. Official trade statistics are available from individual countries, international organizations such as the UN and WTO, and commercial database producers such as Global Trade Information Services (GTIS; Pagell and Halperin 1999). These sources are based on official trade data at the country level, usually collected by customs agencies or national statistics agencies. Of these, GTIS is recognized as the most comprehensive and current (Pagell and Halperin 1999), as it compiles monthly official merchandise import and export data of over 80 countries/regions (GTIS 2015) that covers more than 90% of total international trade (IHS 2014).

Trade is typically measured in volume and value. These metrics have their limitations in that they do not reflect nutritional composition. Analyzing FAOSTAT's country-reported trade data, MacDonald et al. (2015) converted volume of traded food



commodities to calories and found that wheat, soybeans, and maize make up 50% of calories traded but only 21% of nutritional value. Meat and horticultural products, on the other hand, account for a much larger share (44%) of the traded monetary value but a far lower proportion of calories. In addition, the more processed a product is, the higher its value in trade, though the underlying nutritional composition may not be much changed (MacDonald et al. 2015). The current metrics thus provide an incomplete measurement of trade in nutrition.

Assessing carryover stock is challenging when compared with production and trade. Grain stocks stored on-farm or in traders' and millers' warehouses cannot be measured with any degree of reliability, as producers tend to hold on-farm stocks in the hope of obtaining higher prices later in the season, while private companies are unlikely to report the information for commercial reasons (Lynton-Evans 1997). In addition to private stocks, many countries also hold state reserves. China, the world's largest grain stock-holding country, has never released any official data about its reserves and considers this data to be a state secret (Hsu and Gale 2001, Su 2015).

While official trade is relatively straightforward to track, informal cross-border trade is much harder to capture. Exchange is difficult to monitor in small markets that do not participate in international commodity trading (Fafchamps 2004). Informal, or unofficial, unreported trade could represent a significant portion of total trade in some regions, particularly Sub-Saharan Africa. For example, Nkendar (2010) found that Cameroon's unrecorded, informal agricultural exports to neighboring countries in 2008 totaled 38 billion CFA francs, or 96% of the country's official trade. In other words, almost half of the total (official plus unrecorded) agricultural exports from Cameroon were not captured by official trade data. And in Somalia, despite closed borders with both Kenya and Ethiopia, unofficial trade in cattle continued and expanded between 1990 and 2003 (Little 2005). Exchange can also occur within families or ethnic groups in different countries, without being reflected in standard international trade-monitoring mechanisms (Aker et al. 2010, Fafchamps 2004).

Missing trade data not only skews national accounts but can undermine efforts to formulate appropriate policies on issues such as food security, due to incorrect information (Nkendar 2010). The opacity of food exchanged beyond formal bilateral trade mechanisms makes a full evaluation of food availability difficult (Fafchamps 2004).

5.4 Conclusions and the Future

Food availability is determined by a number of factors described in this chapter. Despite the inherent difficulties, it is feasible and prudent to anticipate that the factors determining food availability will not operate in a static fashion, nor will they operate independently of one another. The inclusion of climate change in this discussion adds another set of interacting conditions that precludes highly specific predictions. However, there are tendencies that can be used to understand the pitfalls, barriers, and/or opportunities that a simple, single, path-dependent analysis would not alone allow for, due to the complex set of interconnected operations and processes at work in food systems globally.

This section addresses lessons and conclusions about the future of food availability and its stability, based on the available literature investigations. Subsection 5.4.1 combines information from the rest of this chapter with the shared socioeconomic pathways described in Chapter 3 of this volume, allowing the report's authors to identify sensitivities under climate change given a range of development pathways.

Food availability and its stability over time and space are already being influenced by changes in climate. Food production from crops, livestock, fisheries, and wild game each have climate and weather dependencies that are poised to change, influencing raw food supplies. Packaging, processing, and storage specifications are sensitive to temperature and humidity, and therefore also likely to be influenced. Transportation systems that support trade are subject to climate disruptions as well, limiting the ability for production deficits in one location to be compensated by production excesses elsewhere. When interrupted by climate or other factors, trade disruptions can influence food supplies and their variability. At the same time, large-scale average changes can mask pronounced effects and significant variability at smaller scales (Challinor et al. 2015). Even in scenarios where national agricultural production totals, for example, are unchanged, the conditions experienced by individual producers and consumers can change profoundly.

Food availability and its stability are highly dependent on relatively stable climatic conditions. Changes in the occurrence of weather and climate extremes are already detectable in many regions (Zhang et al. 2011, Coumou and Rahmstorf 2012, Donat et al. 2013, Zwiers et al. 2013, Coumou and Robinson 2013), and even under lower-emissions scenarios, higher frequency of some extremes such

While official trade is relatively straightforward to track, informal cross-border trade is much harder to capture.



as very hot days, very dry days, and intense rainfall events may be anticipated (Tebaldi et al. 2006, Kharin et al. 2007, Wuebbles et al. 2014), which can influence the seasonal availability of food. Variability in food supply is most likely to affect populations that have less capacity to absorb food shortages over short periods of time, potentially increasing the prevalence of transient food insecurity, particularly if increased variability occurs in the absence of increased incomes to compensate for reduced availability through trade mechanisms (Tiwari et al. 2013, Grace et al. 2013, Cornia et al. 2012).

The effect of climate change on crop productivity is projected to be mixed in the near term, with detrimental effects becoming more pronounced and geographically widespread over the longer term and with higher emissions rates (Schlenker and Lobell 2010). A recent meta-analysis of over 1,700 studies found that in the absence of adaptation, losses in aggregate production are expected for wheat, rice, and maize in both temperate and tropical regions at 2 °C higher average growing season temperatures, with adaptive measures improving outcomes substantially (Challinor et al. 2014).

Regional variation is expected and important to food availability. Crop production is expected to increase in high latitudes and decline in low latitudes (Snyder et al. 2001, IPCC 2007c, IPCC 2007a, Ericksen et al. 2010). The geographic center of U.S. production of maize and soybeans, for example, shifted northward by 160–225 km between 1950 and 2010 (Attavanich et al. 2014), and other regional northward shifts have also been observed (Reilly et al. 2003, Olesena et al. 2011, Tolliver 2012). Significant yield decreases are likely in mid-latitude regions of Africa and South Asia, however, particularly under high-emissions scenarios (Schlenker and Lobell 2010, Knox et al. 2012). Hotter average temperatures affect crops by accelerating rates of crop development and evapotranspiration, but extreme temperatures can cause damage that is not typically captured by models, particularly during flowering and the reproduction phase (Gourdji et al. 2013). Mid-latitude regions that already have a high mean temperature may also experience yield reductions if they experience heat waves during the critical period of a crop reproductive cycle (Teixeira et al. 2013).

Regions that already require high water inputs to grow crops are likely to be the first to experience yield reductions where precipitation is reduced (Hornbeck and Keskin 2014). Changes in the distribution and infestation intensity of weeds, insects, and disease will exert additional influence beyond direct temperature and precipitation effects

(Chen and McCarl 2001, Gan 2004, Hicke and Jenkins 2008, Walther et al. 2009, Robinet and Roques 2010). These indirect effects are largely uncaptured by models (Walshall et al. 2012) and affect an operation's anticipated outcomes and adaptive capacity.

All effects are likely to become increasingly pronounced in the latter part of the century, as cumulative emissions grow (Rosenzweig et al. 2014). To 2050, most studies show a small average crop yield decrease globally from a changing climate; this is true even for high-emissions scenarios, because over that relatively short timescale, projections are similar (Rosenzweig et al. 2014). Beyond that, the projections diverge demonstrably based on scenario and changes are more readily discernible, with more-detrimental outcomes expected for higher emissions scenarios (Challinor and Wheeler 2008).

Livestock operations in regions requiring high water inputs are likely to be the first to experience livestock production reductions associated with climate change (Hornbeck and Keskin 2014). Differing responses are expected in different types of livestock systems (Seré and Steinfeld 1996). Mixed crop/livestock systems may face trade-offs between land and water allocations for their crops and for livestock, including the need to supply feed that may have been grown and purchased elsewhere rather than grown on-site (Thornton et al. 2009). Such choices will be influenced by economic and cultural considerations, and prices and property ownership will alter available management alternatives. The design of animal-housing facilities may increasingly need to take disease and pest occurrences into account, and the nutritional needs of the livestock may shift. Trade-offs made between income, food security, and environmental objectives in the livestock sector will influence future outcomes (Thornton et al. 2009).

Fish protein will remain important in coming decades, particularly for low-income and vulnerable populations (HLPE 2014). As fishery management develops characteristics of terrestrial food production and relies increasingly on aquacultural methods over wild-caught fish, the ability to adapt to changes in climate is likely to improve (Boyd and Brummett 2012, World Bank 2013). The World Bank (2013) projects 2% annual average increases in aquaculture fish production between 2010 and 2030, though considerable uncertainties exist (Brander 2007).

The availability effects of changing fish distribution and abundance from changing water temperatures and chemistry in the coming decades therefore depends on the vulnerability of the communities



Fish protein will remain important in coming decades, particularly for low-income and vulnerable populations



who rely on the fish as a dietary protein source. Because poorer and less empowered countries and individuals tend to rely more heavily on fish protein, these countries and individuals are more vulnerable to climate effects on production, and the fisheries they rely upon are more likely to be overexploited (FAO 2007). Overexploitation of fisheries is a likely outcome of anticipated changes in climate, particularly fisheries that supply those who are poor and depend more upon fishery resources for food and incomes (FAO 2007).

Changes in the role of wild game as a food-security safety net in coming decades depend in large part upon the functioning of the natural-resource base in the forest, coastal, and savanna systems where wildlife lives (Dahdouh-Guebas et al. 2005, Patz et al. 2004). Where development is limited and wildlife populations remain viable, the harvest rates of wild game may increase, unless other forms of livelihood can be ensured (FAO 2008a).

The changing climate imposes new stressors on current and future food production in many important agricultural regions, possibly leading to an increase in production volatility. The most immediate effects will emerge in the low latitudes where interannual variability is comparatively low, causing changes in availability and pricing (Parry et al. 2004, Lobell et al. 2011). Temperature changes that lead to shifts in the location of optimal growing areas may lead to changes in the availability of certain food types, trade patterns, and pricing. Through mid-century, changes are not expected to be pronounced at the average global scale, regardless of the specific emissions trajectory. High-emissions scenarios are expected to result in disproportionate increases in damaging outcomes.

Land degradation, loss of ecosystem services, and increased vulnerability of rural communities have resulted in the overappropriation of the natural-resource base that forms the foundation of food production (Haberl et al. 2007, Power 2010, Lambin and Meyfroidt 2011, Eshel et al. 2014). A focus on individual goals to the exclusion of others can lead to perverse outcomes through the degradation of ecosystem services that undermine the sustainability of the land-use system, disrupt social structures, affect livelihoods, and lead to unintended consequences in other parts of the globe (Ojima et al. 2009). The degree of integration in land management



in a world of rapidly growing human population and per-capita consumption of ecosystems services is highly context-dependent and will influence food production, livelihoods, and their sustainability (Haberl et al. 2007, Seto et al. 2012, Ojima et al. 2013, Tschakert et al. 2008).

Future food availability during climatic shifts and stresses is largely determined by adaptive capacity within the food system and dependent in many ways upon choices made by food-system actors. Climate-controlled food-storage infrastructure, road systems, and market structures that lack adequate supply during the months preceding harvest are important determinants (Vermeulen and Campbell et al. 2012, Hillbruner and Egan 2008, Handa and Mlay 2006), and how each is managed will influence outcomes. Lower-emissions scenarios with more moderate temperature increases would require fewer large-scale changes than higher-emissions scenarios.

Much can be done to adapt to these changing conditions, as each of these sectors has a great deal of potential technical capacity for flexibility. However, adaptation may not be feasible due to informational, societal, or financial constraints, and overall adaptive capacity must be considered with respect to these considerations.

5.4.1 Food Availability and Stability in the Context of Shared Socioeconomic Pathways (SSPs)

Climate change affects food availability through its key food-system elements, with differing effects under differing socioeconomic trajectories.



Future food availability during climatic shifts and stresses is largely determined by adaptive capacity within the food system and dependent in many ways upon choices made by actors within the food system.

| Shared Socioeconomic Pathway | Production | | Storing/Processing/ Packaging | | Trade | | Transport | |
|------------------------------|-----------------|-----------------|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | P | W | P | W | P | W | P | W |
| SSP1 | Low Risk | Low Risk | Low Risk | Low Risk | Low Risk | Low Risk | Low Risk | Low Risk |
| SSP2 | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk | Medium/Low Risk |
| SSP3 | Medium Risk | Medium Risk | Medium Risk | Medium Risk | Medium Risk | Medium Risk | Medium Risk | Medium Risk |
| SSP4 | High Risk | High Risk | High Risk | High Risk | High Risk | High Risk | High Risk | High Risk |
| SSP5 | Very High Risk | Very High Risk | Very High Risk | Very High Risk | Very High Risk | Very High Risk | Very High Risk | Very High Risk |

(P: poorer nations, W: wealthier nations)

| Key |
|-----------------|
| Low Risk |
| Medium/Low Risk |
| Medium Risk |
| High Risk |
| Very High Risk |

Figure 5.3 Relative risks to key food availability elements for different SSPs. The risks to food availability would be lowest under the economic conditions described by SSP1 and SSP5, with poorer nations at higher risk across all food production, distribution, and trade categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report, based on the available literature.

To illustrate the range of possible outcomes, this section considers food production, trade, transport, storage, packaging, and processing for each of the shared socioeconomic pathways (SSPs) introduced in section 3.4.1 of this volume. Many parts of the food system are not considered by the SSPs or by available modeling frameworks directly; however, this discussion reflects the informed judgment of this report's authors based upon the literature discussed previously in this chapter (Figure 5.3).

Producing Food

The risks to crop production posed by climate change would be greatest under SSPs 2, 3, and 4. Under these scenarios, as yield increases weaken due to reduced agricultural investment and increasing land degradation, extensification onto arid land and areas with more-variable climate is likely to continue or increase. This trend exposes producers to more-variable and limiting climate conditions. It is therefore likely that under SSPs 2, 3, and 4, variability in temperature and rainfall would increase challenges to local availability for some areas. Under SSPs 3 and 4, this challenge could be particularly pronounced, as those living in the poorest countries under these scenarios are likely to lack access to agricultural technologies that could offset some climate-variability effects on production in more-arid and marginal lands.

The risks posed by climate change to crops would be lowest for SSPs 1 and 5. Under these SSPs, gradual intensification would likely be the principal means of increasing yields. With technological investment and development seen as high priorities, extensification is unlikely to take place in a manner that results in increased production in arid or highly variable environments, lowering the overall exposure of crops to climate stressors under these scenarios.

Patterns of climate-related stress on livestock production under the different SSPs are similar to the patterns seen for crops, in part because livestock husbandry depends upon crops for feed in many regions. Wealthy countries, with robust economies and food-production systems would have livestock-

production systems that are more resilient than those in poorer countries. Under SSP1, although incomes rise, the rate of increase in livestock production and consumption slows as society shifts toward less-resource-intensive means of generating calories. That shift, driven by broadly held societal goals of greater sustainability, leads to a livestock sector closely tied to locally available resources. Under SSP5, relatively open markets and strong investment in technologies to address climate-change effects would likely manage most anticipated effects on livestock production. However, the increased likelihood of climate-change effects that exceed technological solutions makes agricultural production under this scenario more precarious than under SSP1.

The remaining three scenarios present more-significant challenges for agricultural production and demonstrate that those in wealthy countries are not immune from potentially damaging climate-change effects. Under SSP2, imperfect markets and increasing environmental degradation would likely affect feed prices, making production of cattle and large ruminants less economically sustainable. Under SSPs 3 and 4, markets function even more poorly, making it nearly impossible to effectively smooth out the price impacts of climate shocks that affect local feed supplies. Such events may force at least temporary reductions in herd size and could result in the abandonment of the husbandry of particular animals.

Processing, Packaging, and Storing Food

Under nearly all SSPs, climate change is expected to have limited effects on the storage, processing, and packaging of food in wealthy countries. In poorer countries, however, different SSPs produce different outcomes. Under SSPs 1 and 5, investments in education and health generally lead to more-hygienic and reliable food storage, processing, and packaging. These outcomes appear more durable under SSP1, where the increased focus on human well-being creates broader societal conditions under which food storage, processing, and packaging are seen as important contributions to well-being, and investments in these processes and technologies



outstrip the effects of climate change. Under SSP5, food-safety gains are predicated on the generation of wealth through the consumption of fossil fuels, which over time are likely to lead to significant climate changes and shocks that can undermine education and health investments under those pathways. In both cases, improvements to food storage, processing, and packaging can help to maintain or even improve food availability and stability, even with climate change.

Under SSP2, there are fewer investments in education or health, and a limited social emphasis on human well-being as a metric for successful policy outcomes. Investments in food storage, processing, and packaging proceed unevenly and slowly, exposing populations to increased levels of unsafe food. Under SSPs 3 and 4, investments in education and technology decline over time relative to other concerns. As poorer countries struggle to provide safe water, improved sanitation, and appropriate health care to their populations, the changing climate would expose weaknesses in food storage, processing, and packaging that contribute to unsafe or low-quality food. Under SSPs 2, 3, and 4, climate change is more likely to lead to higher rates of spoilage and contamination.

Trading and Transporting Food

Under SSPs 1 and 5, world markets would be highly connected and trade would flow easily between countries and regions. Under these scenarios, markets are likely to be able to facilitate the movement of food from areas of surplus to areas of deficit. This is likely to smooth food availability and stability challenges created by changes in climate under either of these scenarios.

SSPs 2, 3, and 4 all present different futures under somewhat constrained global trade. Under SSP2, stresses and shocks in availability are anticipated, and the semi-open globalized economy may not be open enough to facilitate the robust trade links needed for markets to effectively respond to these shocks. Under SSPs 3 and 4, this pattern is accentuated. These SSPs present a world where the wealthy enjoy strong trade connections through which they can access goods and resources, but have few connections to the global poor, and the poor have few connections between one another. As a result, markets would rarely respond fully to shocks and stresses on availability such that food can effectively move into deficit areas to address shortages. Under SSP3, poor market connectivity also exists among the wealthy of the world, though effects on food availability would almost certainly be less severe than among the poor because greater incomes allow for greater food access (Chapter 6). Under SSP4, high within-country inequality could

create market-based challenges that diminish food availability for segments of the population within a country. For example, the consumption of meat and other resource-intensive foods under this scenario would divert food away from poorer populations, and low-functioning markets would inhibit trade to areas of deficit created by this pattern of consumption.

Under SSPs 1 and 5, high rates of economic growth facilitate the construction of transportation systems that enable effective food trade. Under SSP1, transportation systems would be designed with future climate conditions in mind for better robustness over time; under SSP5, some of the high-consequence impacts of climate change are considered in their design. Under SSP5, heavy reliance on fossil fuels to drive economic growth could accelerate observed changes in the climate over the next few decades, resulting in damage to physical infrastructure, such as flooded ports and roadways. Under such a scenario, poorer countries would have fewer resources and therefore a lower capacity to address impacts.

SSPs 2, 3, and 4 would see uneven transportation outcomes, with wealthier countries better able to maintain infrastructure, and poorer countries less able to finance needed improvements, repairs, or retrofits that might address climate change.



